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Laser Catheter Coagulation of Normal and Scarred Ventricular Myocardium in Dogs

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Background and Objective: **Larger lesions would increase success rates of catheter ablation of ventricular arrhythmias. Therefore, improved radio frequency current application techniques, but also alternative energy sources, are being investigated. The purpose of this study was to determine morphology and dimensions of ventricular lesions induced by transcatheter application of laser energy.**
Material and Methods: **A total of 244 lesions were produced by Nd:YAG laser pulses, 1,064 nm, 10–30 W, 15–60 s, percutaneously (endocardial approach, n = 124) and under visual control (epicardial approach, n = 120) in the left ventricular walls of 24 anesthetized dogs.**
Results: **Dimensions of lesions increased with the amount of energy applied. Maximal values were obtained at 20 W, 60 s: depth = 12.6 ± 1.1 mm (transmural); width = 15.0 ± 2.8 mm; volume = 1,582 ± 777 mm^3. Volumes of lesions did not change significantly when induced through previously scarred myocardium. Histologically, lesions were clear-cut, without crater or thrombus formation. Procedures and follow-up periods of up to 22 months were without complications.**
Conclusion: **Nd:YAG laser pulses at 10–20 W and 15–60 s produce homogeneous myocardial lesions of coagulation necrosis of reproducible sizes, in a controllable manner, without unwanted effects on the ventricular walls, in normal and through scarred myocardium of dogs. The laser method is a promising alternative for ablation of ventricular arrhythmias including candidates with ischemic heart disease. Lasers Surg. Med. 14:109–119, 1998.**

Key words: catheter ablation; laser; lesion; ventricle

INTRODUCTION

Radiofrequency (RF) catheter ablation techniques have revolutionized the therapy of supraventricular tachycardia, particularly of those caused by the Wolff-Parkinson-White syndrome and atrioventricular nodal reentry [1–3]. RF energy also has offered a new therapeutic alternative for selected patients with ventricular tachycardia (VT). Appropriate arrhytymias include idiopathic monomorphic VT in patients without structural heart disease [4,5] and VT caused by bundle branch reentry [6,7]. However, the major-

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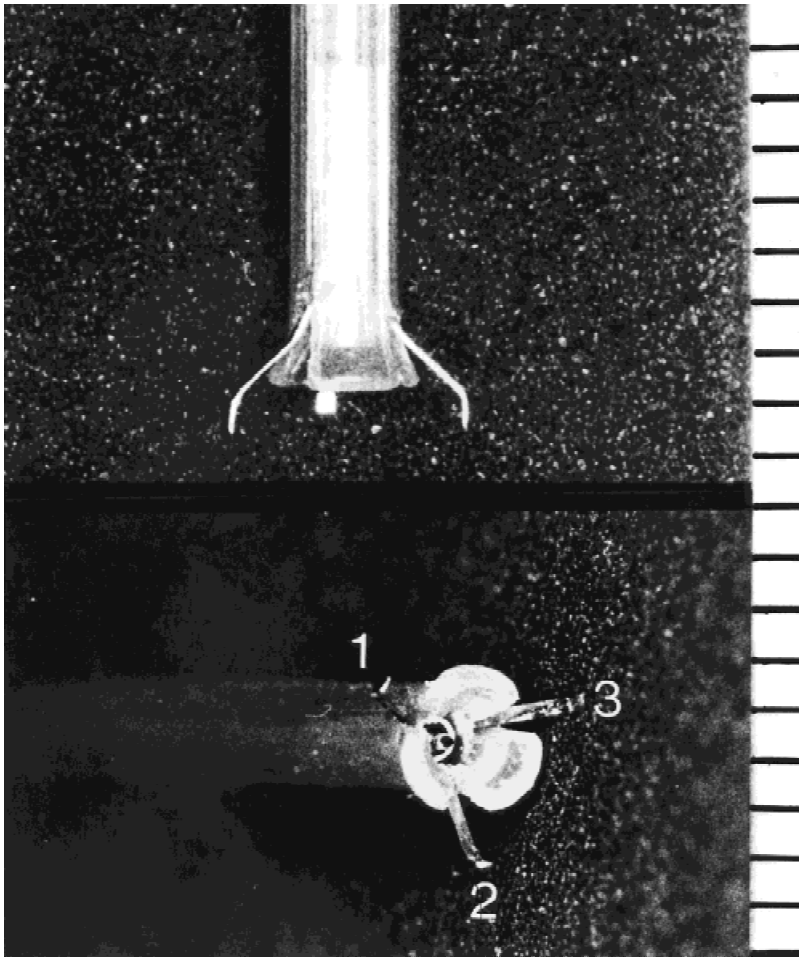

Fig. 1. Lateral (top) and oblique (bottom) view of the distal end of the pin-electrode laser catheter showing the pins 1, 2, and 3 in straddling position, the slits running distally from each pin and the optical fiber mounted in the central lumen; millimeter scale on the right margin.

ity of patients who present with sustained VT have structural heart disease. Of these, most have coronary artery disease, although some suffer from dilated cardiomyopathy. The RF ablation success rate in these patients is but 66–68% [8]. In order to improve the results and reduce serious complications, investigation in the field of VT ablation is very active. Areas where there is currently a high level of interest include attempts to improve targeting of VT, to improve the ease of catheter manipulation, and to allow for increase of lesion size. In addition, alternative energy sources such as microwave, ultrasound and laser light are being investigated.

Successful intraoperative mapping-guided laser ablation of arrhythmogenic myocardium in patients with drug-resistant VT including VT due to myocardial infarction was reported [9,10]. Recently, a novel laser catheter system was successfully used for ablation of supraventricular tachycardias [11–14]. The aim of this study was to assess: (1) handling and maneuverability of this catheter system upon various ventricular areas in the beating canine heart, (2) dosimetry of lesions, and (3) the electrocardiographic and morphohistopathologic acute and chronic sequelae of laser application on normal and scarred left ventricular myocardium in dogs.

MATERIALS AND METHODS

Catheter System

Laser light was applied via a custom-made catheter system that consists of: (1) 9 French (F) guide catheters with a central lumen of 7 F, straight or with preshaped curves at their distal end as follows: the first curve had a radius of 30 mm and an angle of 90° (type A) or 180° (type B) followed toward the endhole, in a vertical plane, by a second curve with a radius of 20 mm and an angle of 90°, (2) a 7 F electrode laser (EL) catheter with a central lumen of 1 mm and an endhole; its distal end was provided with three resilient pin-electrodes and three slits (Fig. 1), and (3) a flexible optical fiber with a 0.4 mm core diameter fed

into the central lumen of the EL catheter and attached to the distal catheter section in a coaxial position to keep the fiber tip at a constant distance of ~1.5 mm from the endhole. Thus the optical fiber was kept inside the catheter hose and contact of its tip with the targeted surface avoided. Depending on the desired lesion morphology, the fiber tip had either a flat surface or a conical shape. The flat surface resulted in a beam divergence of 15° and an irradiation spot of 0.7 mm in diameter with a Gaussian-like intensity profile and was used for induction of fingerlike scars in the myocardium. The conical tip ground to a taper angle of 33° increased the beam divergence to 70° and created a ring-shape irradiation field with a diameter of 2 mm. This fiber was used for the endocardial and epicardial dosimetry studies. The space between the lumen of the catheter and the optical fiber was used for flushing with heparinized saline.

Laser and Flushing System

The optical fiber was coupled to a 1,064 nm continuous wave Nd:YAG laser. The distal laser power and pulse duration were varied from 10–30 W and 15–60 s. A rolling pump connected to the proximal end of the catheter was used for continuous flushing with saline, 18–20°C, at a rate of 6 ml/min that was augmented to 60 ml/min automatically via the laser foot switch when laser energy was delivered.

Ablation Procedures

Twenty-four healthy 12–19 kg beagles of either sex were anesthetized by i.v. Thiamylal-Na 4%, 0.4 ml/kg and intubated for isofluran (0.8–1.5%) and nitrous-oxide anesthesia. Heart rate, quality of peripheral pulse, and arterial oxygen saturation were monitored throughout the procedure. A total of 244 lesions, 9–14 per dog, endocardial approach 124 and epicardial approach 120, were produced. The first catheterization procedure was performed to produce a fingerlike lesion by one laser application in the left ventricular apex. The procedure was repeated after 3 months in order to produce a second fingerlike lesion crossing through the apical scar. After another 3 months, the endocardial dosimetry study was performed on the lateral and posterior left ventricular free walls. Subsequently, 12 dogs were allowed to recover from anesthesia for a follow-up of 3–4 days (6 dogs, subacute lesions) or 6–22 months (6 dogs, chronic lesions). For the epicardial dosimetry study, lesions were produced under visual control on the anterior region of the left ventricular free wall following immediately the endocardial approach (12 dogs) or at the end of follow-up.

Scar model. Under sterile conditions and X-ray control, a guide catheter was inserted through the femoral artery (Seldinger technique or cut-down) and was advanced over a guidewire retrogradely via the aortic valve and positioned in the left ventricular apex. The wire and the dilator were then removed and in order to obtain a fingerlike laser lesion, an EL catheter with an optical fiber of low beam divergence was inserted and advanced beyond the end hole of the guide and was brought in contact with the endocardial surface. Acting as a tripod, the spread-out distal end of the EL-catheter hose stabilized its intracardiac segment in an approximately perpendicular position on the pulsating ventricular wall in the beating heart. Via the pin-electrodes of the EL catheter, three bipolar intracardiac electrograms could be recorded from around the irradiated spot of the targeted endocardial area. Intracardiac together with surface electrocardiograms lead I, II, aVR, aVL, and aVF were selectively displayed and recorded at paper speeds of 10–100 mm/s. After one laser pulse of 10 W, 15 s the catheter was removed and the animal was allowed to recover from anesthesia. After 3 months, the procedure was repeated and a second laser pulse of 10 W, 15 s was aimed at the apical region in order to obtain crossing lesions (Fig. 2, left). Besides X-ray control, low amplitudes of local potentials always present in the scarred regions were useful markers for localization of the second application of laser energy.

Endocardial dosimetry. After another 3 months, preshaped guide catheters of type A and B were used to direct an EL catheter with high beam divergence toward discrete regions of the lateral and posterior left ventricular free wall (Fig. 2, right). Laser pulses were applied under X-ray control at distances of at least 20 mm from each other in order to avoid overlapping of lesions. Appropriate catheter positions were additionally verified by local potential recording via the pin-electrodes as low amplitudes indicate previously irradiated regions of myocardial coagulation necrosis. Effectiveness of laser application was controlled by means of the electrograms recorded from around the targeted area via the pin-electrodes. If the local potentials did not decrease within the first 5 s of irradiation, the pulse was terminated prematurely and the catheter was re-

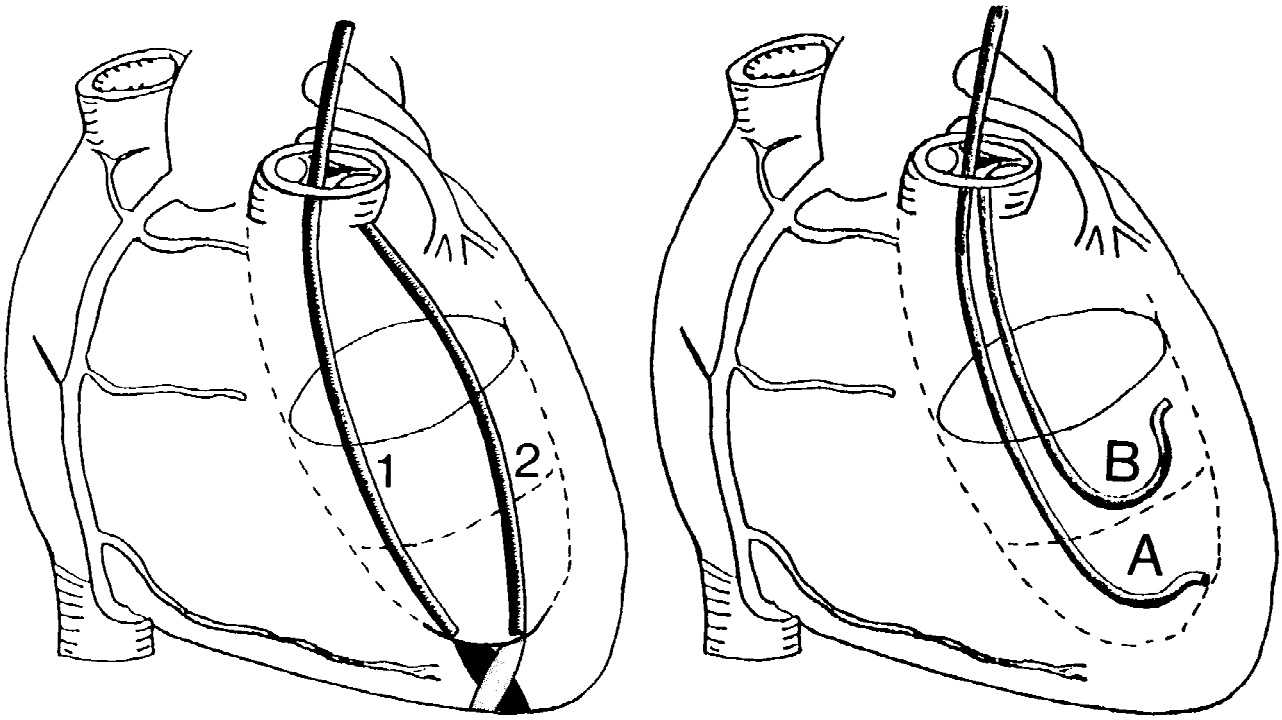

Fig. 2. Left: Position of straight guide catheters during laser irradiation of apical regions. The first lesion was produced with the guide supported by the interventricular septum (1) and with the laser beam orientated from the septal toward the free wall region. The second lesion was produced 3 months later with the guide positioned along the free wall (2) in order to achieve crossing lesions (shadowed areas). Right: Position of guide catheters of Type A and B in the left ventricular cavity for anatomically guided laser pulses aimed at various endocardial areas.

positioned. After each laser pulse, the EL catheter was removed for visual inspection. For endocardial dosimetry a total of 100 lesions were produced as follows: 18 lesions at a laser power of 10 W and pulse durations of 15, 30, or 60 s (acute: n = 6 each); 22 lesions at 20 W, 15 s (acute: n = 8, subacute: n = 6, chronic: n = 8); 24 lesions at 20 W, 30 s (acute: n = 8, subacute: n = 8, chronic: n = 8); 24 lesions at 20 W, 60 s (acute: n = 16, subacute: n = 4, chronic: n = 4); 6 acute lesions at 25 W, 30 s and 6 acute lesions at 30 W, 30 s. Electrocardiographic monitoring was performed for 3–24 h followed by daily clinical control and 6-lead electrocardiograms for 1 week and weekly controls for the remainder period.

Epicardial dosimetry. Hearts were exposed through a medio-sternal thoracotomy. Under visual control, a hand-held EL catheter with high beam divergence was placed perpendicularly upon and maintained stationary relative to the epicardial surface of the beating heart. Epicardial coronary vessels were spared from the procedure. A total of 120 laser pulses, 4–8 per dog, at distances of 30–40 mm from each other, were aimed at the anterior region of the left ventricular free walls. In order to avoid overlapping with endocardial lesions, laser pulses of low energy were applied on hearts irradiated with high energy pulses during the endocardial approaches and vice versa. Three hours after the epicardial procedures, KCl iv was administered. After death, the hearts were removed and rinsed with saline.

Pathology and Statistics

After visual inspection of the entire heart, the right ventricle was removed, the interatrial and ventricular septum incised, and the left heart widely opened. After detailed visual inspection of the entire endocardial surface of the left ventricular cavity and of the mitral valve and chordae, lesions were evaluated morphometrically. Transmural incision through the lesion center was performed and maximal depth and diameter were measured. Lesion volume was calculated by use of the formula for an ellipsoid:

$$\text{Volume} = 4/3 * \pi * \text{Depth}/2 * (\text{Diameter}/2)^2$$

Data were expressed as mean values ± standard deviation (SD). Student's t-test was used to com-

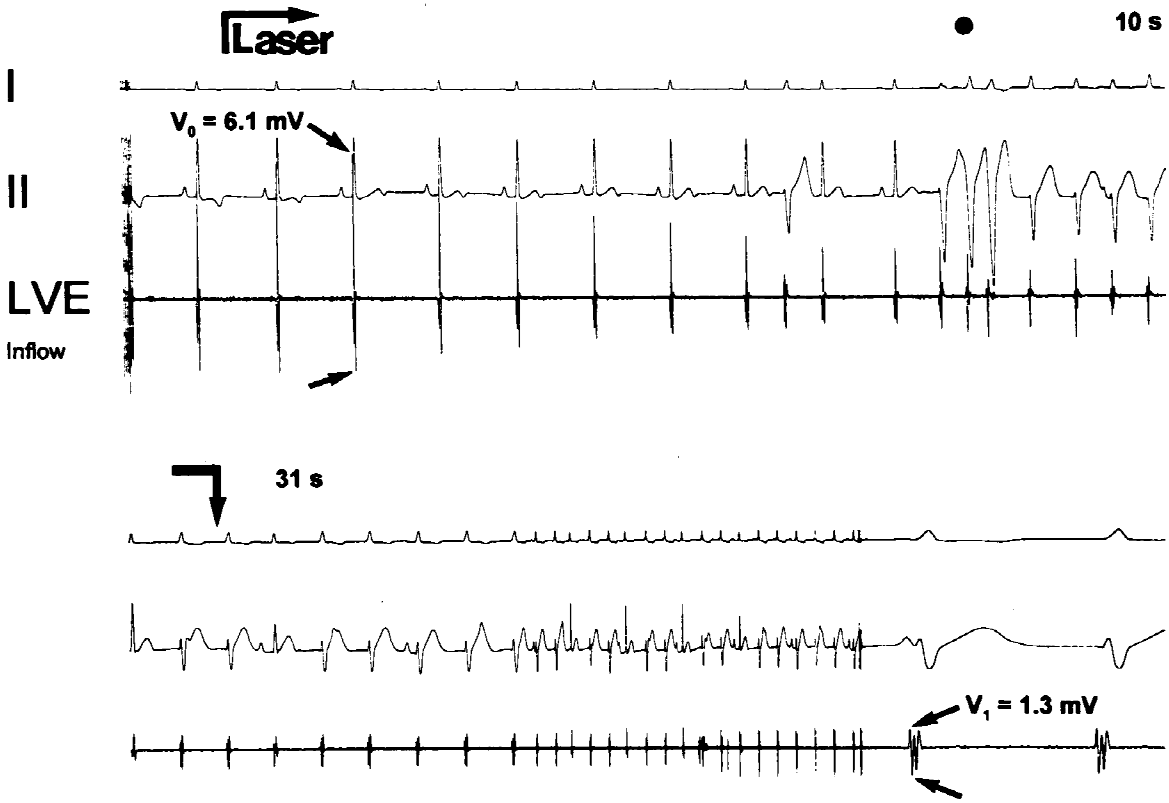

Fig. 3. Electrocardiographic leads I, II, and local endocardial electrogram (LVE) recorded via the electrode laser catheter during a laser pulse aimed at the inflow tract of the left ventricle in a dog showing (1) gradual weakening of local potentials with the onset of the pulse, (2) a triplet occurring simultaneously with an audible pop (dot) in the 8th second of the laser pulse, and (3) persistence of left axis deviation after the pulse.

pare gross pathology measurements. A value of $P < 0.05$ was considered statistically significant. After photodocumentation, the hearts were fixed in formalin for 3–5 days. Paraffin-embedded blocks containing the lesions were sectioned and stained with hematoxylin-eosin and van Gieson alternately.

RESULTS

The endocardial procedures, from the beginning of anesthesia until removal of catheters, were completed in 91–144 min (average 110). Visual inspection of the EL catheter revealed no blood clotting or debris of tissue on the tip. Total X-ray irradiation time was 7.1–27.4 min (average 12.9) per study. All animals survived the experiments without complication and follow-up periods were uneventful.

Electrocardiographic Observations

During effective pulses, the amplitudes of the local potentials weakened progressively from 6.5 ± 1.2 to 1.5 ± 0.3 mV. They decreased persistently to <15% of the initial value during 112 (46%) and to <15–50% during 132 (54%) applications. Six applications were initially ineffective. These pulses were ended prematurely after 5–7 s and repeated after reorientation of the catheter under X-ray control. Laser pulses were invariably associated with ventricular extrasystoles and with occasional runs of nonsustained VT. Isolated ventricular extrasystoles were noted during 106 (43%) applications. Runs of nonsustained (<30 s) VT were present during 19 pulses aimed at the inflow tract regions and during 2 pulses aimed at the apical ventricular regions regardless of type of approach or the amount of energy applied. Complex ventricular arrhythmia occurred during 4 endocardial laser pulses following audible pops: in the 28th second at 25 W and in the 8th, 24th, and 29th second at 30 W. Deviation of the ventricular electrical axis was present after one of these pulses (Fig. 3). During the epicardial pulses, audible pops occurred in the 30th second of a pulse at 25 W and in the 24th and 28th seconds at 30 W. No

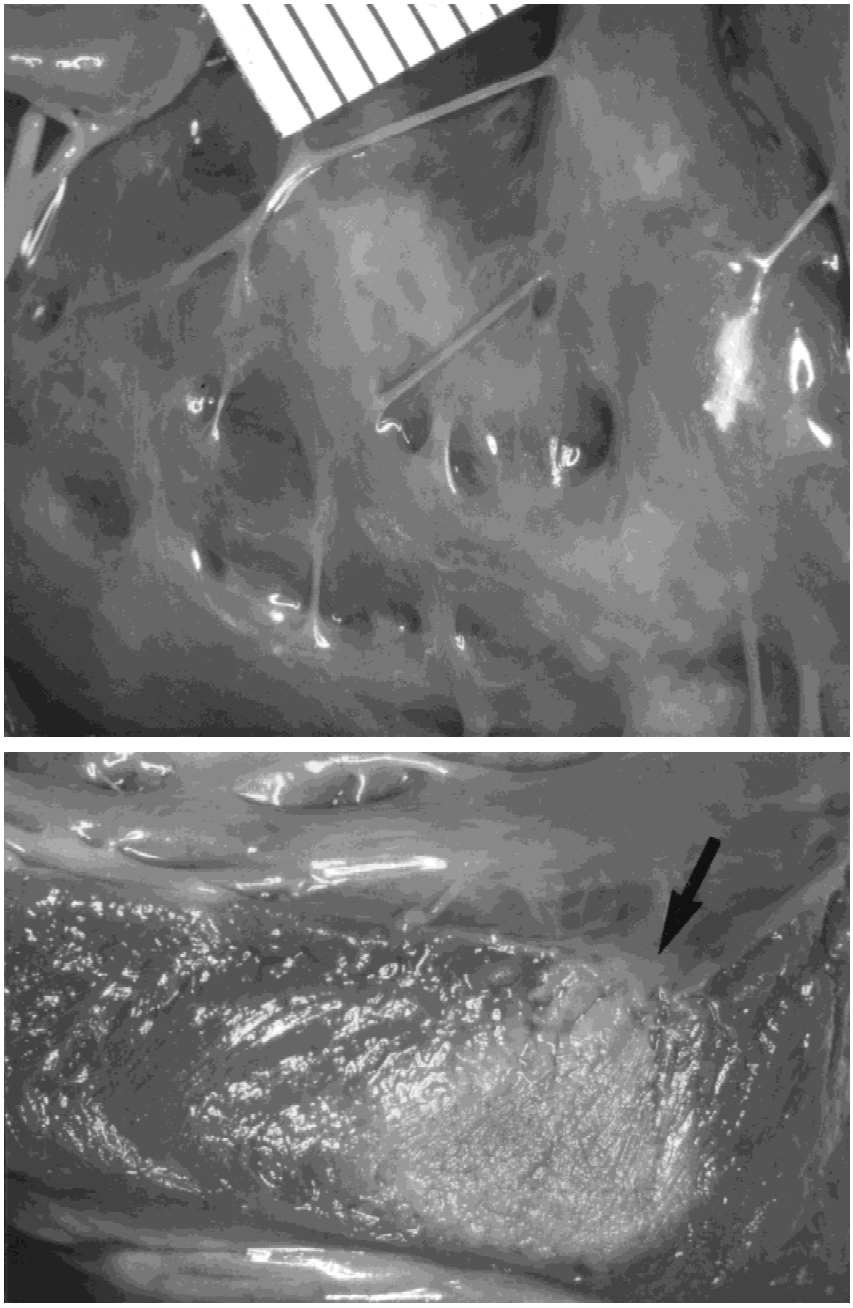

Fig. 4. Endocardial view (top) and longitudinal section (bottom) of a three hours old acute transmural lesion produced by an endocardial laser pulse at 20 W and 60 s aimed at the left ventricular free wall in a dog showing continuous endocardium and preserved chordae in the irradiated field. Arrow: assumed orientation of the laser beam.

audible pop was noted during laser pulses at 20 W or less. During follow-up isolated atrial and/or ventricular extrasystoles were documented in the electrocardiograms.

Gross Pathology

There was no tissue vaporization and crater formation. The continuity of the endocardium and epicardium was always preserved, including the lesions accomplished by laser pulses with concomitant audible pops. Lesions of coagulation necrosis were always sharply demarcated (Fig. 4). The *apical lesions* were fingerlike and transmural. In 16 dogs, the apical scars were crossing through each other approximately in their midportion (Fig. 5). The sizes of the crossing scars did not differ significantly from each other. Dosimetry was evaluated exclusively from lesions produced with the high divergence laser beam. *Epicardial* laser coagulation resulted in circular whitening of the epicardial surface around the catheter tip. The maximal lesion diameter was at 3.8 ± 0.4 to 6.1 ± 0.9 mm below the surface. No overlapping of lesion boundaries was seen. Maxi-

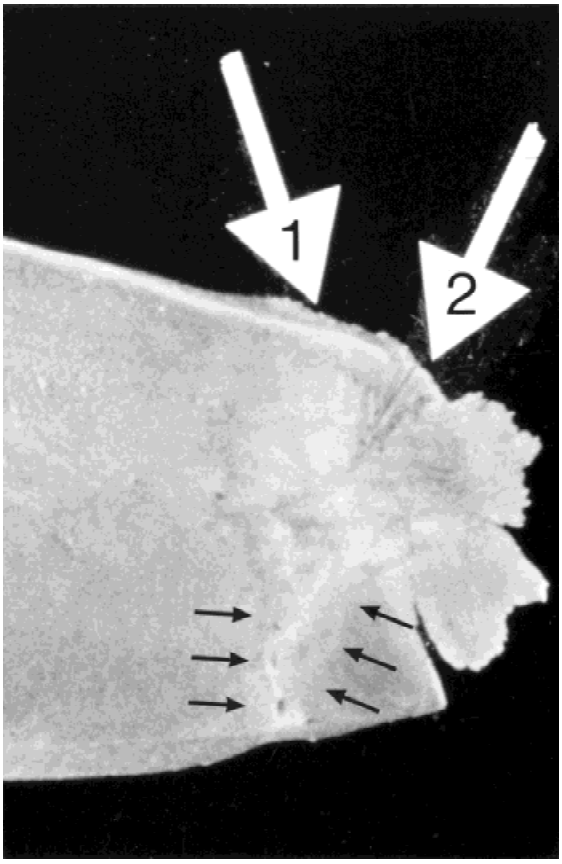

Fig. 5. Sectional view of a crossing lesion in a dog heart showing the 3 and 6 months old apical scars produced by transcatheter laser pulses of 10 W, 15 s each. The scars are crossing through each other approximately in the midportion of the transmural spread of fibrosis. White arrows: assumed direction of the first (1) and of the second (2) laser beam. Black arrows indicate the fibrosis produced through the preexistent scar.

mal diameter, depth, and volume increased with the amount of energy applied. Transmural lesions were obtained at energies above 450 J (Table 1). Lesion depth was limited by myocardial thickness (Fig. 6). Maximal dimensions of *endocardial* lesions were obtained at 20 W, 60 s. Volume of endocardial lesions did not differ significantly from epicardial values. Dimensions of acute and subacute lesions did not differ significantly from each other. Volumes of chronic lesions showed tendency of shrinkage and were approximately 20% smaller ($P > 0.05$) than the acute lesions (Table 2). There was no aneurysm or mural thrombus formation.

Histology

Acute lesions were homogenous and sharply demarcated. The endocardium and epicardium was always continuous. In some instances there was slight edema and splitting, occasionally with little fibrin. The area of coagulated myocardium showed loss of striation with picnotic nuclei and hypereosinophilic cytoplasm surrounded by myocardium characterized by contraction band formation in all the cardiac muscle cells. The nuclei and the interstitium looked normal. Completely normal myocardium surrounded the damaged tissue. The border between normal and damaged myocardium was clear-cut. There was no charring or thrombus formation. The total tissue volumes remained intact. Trabeculations, mitral valve, and papillary chordae remained undamaged. In general, a thin subendo- or subepicardial rim of <1 mm was spared. Coagulation lesions were occasionally bent along intramural vessels. The fine structure of the coronary arteries and veins found within the coagulation zones was preserved and there were no intraluminal thrombi seen. Dissociation of fibers and intramural hemorrhage surrounded by edema were present only in the centers of acute and subacute lesions with an audible pop during irradiation. Subacute lesions were characterized by zonal structure. Necrotic myocardium in the central area was surrounded by edema. Interstitial hemorrhagic and inflamma-

TABLE 1. Dimensions ± SD of Epicardial Lesions (n = 8–12) in Correlation With Amount of Energy Applied

Energy (J)	Power (W)	Pulse length (s)	Width (mm)	Depth (mm)	Volume (mm^3)	Transmural lesions
300	10	30	7.4 ± 0.8	8.2 ± 0.8	235 ± 55	0
300	20	15	8.4 ± 0.7	7.7 ± 0.5	287 ± 45	0
450	15	30	9.8 ± 0.9	9.0 ± 0.9	453 ± 104	0
600	10	60	10.7 ± 0.8	10.7 ± 0.7	646 ± 107	2
600	20	30	11.3 ± 1.0	10.9 ± 1.1	732 ± 156	3
675	15	45	11.9 ± 1.4	10.5 ± 1.0	797 ± 216	2
750	25	30	12.2 ± 0.9	10.9 ± 1.1	855 ± 164	1
900	15	60	13.0 ± 0.8	11.5 ± 0.9	1,014 ± 137	6
900	20	45	12.8 ± 1.7	10.9 ± 1.0	958 ± 298	7
900	30	30	13.2 ± 2.2	11.2 ± 1.2	1,055 ± 476	7
1,200	20	60	14.7 ± 2.0	12.3 ± 1.3	1,420 ± 465	8

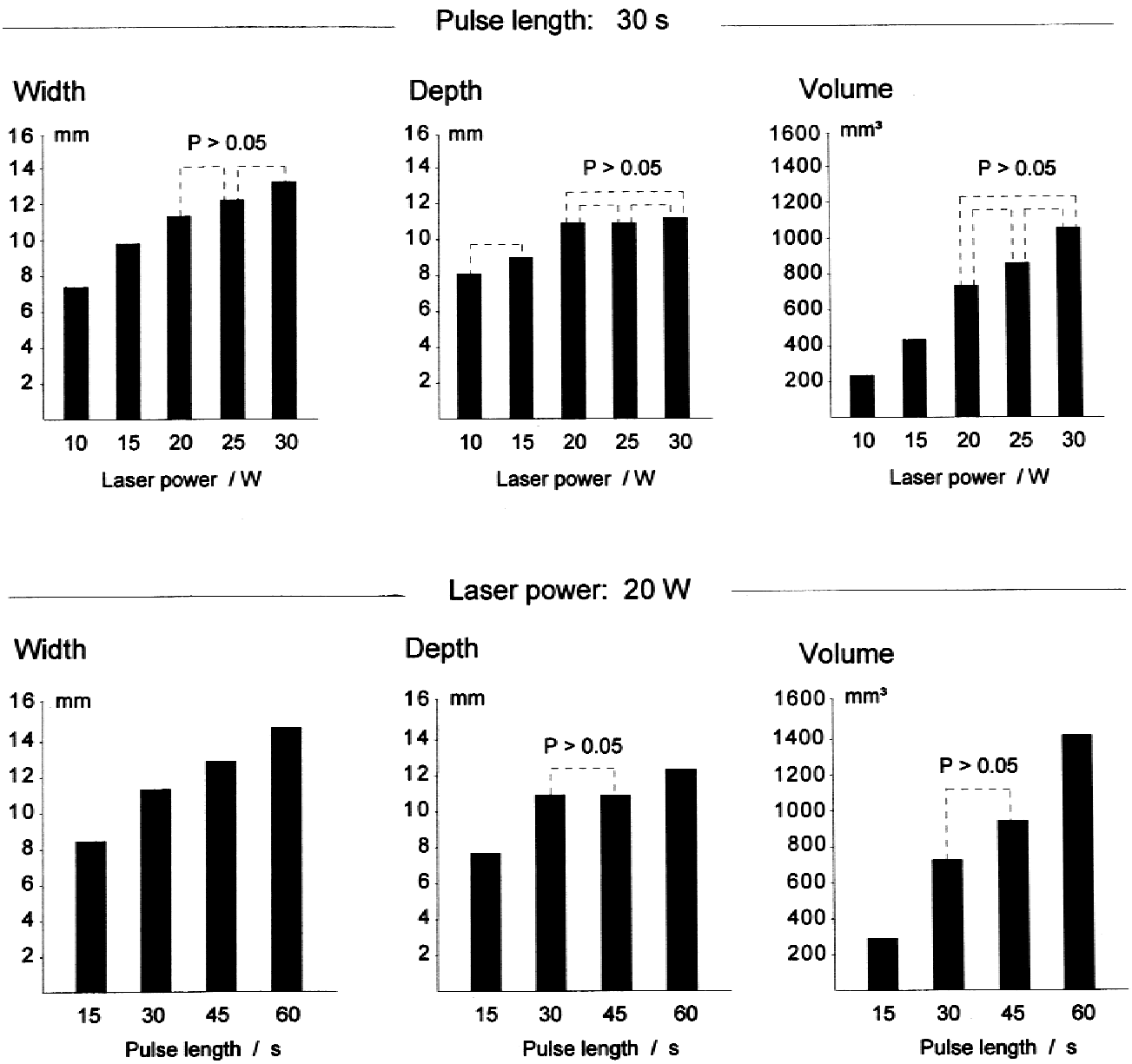

Fig. 6. Bar graphs showing width, depth, and volume of acute epicardial lesions produced in the left ventricular free walls of dogs at various laser powers (top) or pulse lengths (bottom). Values differ significantly from each other except where indicated by broken lines.

TABLE 2. Dimensions ± SD of Endocardial Lesions (n = 8 each, except for 1,200 J, n = 16) Produced by Transcatheter Nd:YAG Laser Pulses of 20 W and Various Lengths in Left Ventricular Free Wall of Dogs

Lesion type	Pulse length (s)	Energy (J)	Width (mm)	Depth (mm)	Volume (mm^3)
acute	15	300	9.5 ± 1.0	7.2 ± 0.7	344 ± 81
acute	30	600	11.3 ± 1.2	11.0 ± 1.1	735 ± 145
acute	60	1,200	15.0 ± 2.8	12.6 ± 1.1	1,582 ± 777
subacute	30	600	11.8 ± 1.5	10.8 ± 1.0	796 ± 175
chronic	30	600	10.4 ± 1.4	10.1 ± 1.2	575 ± 166

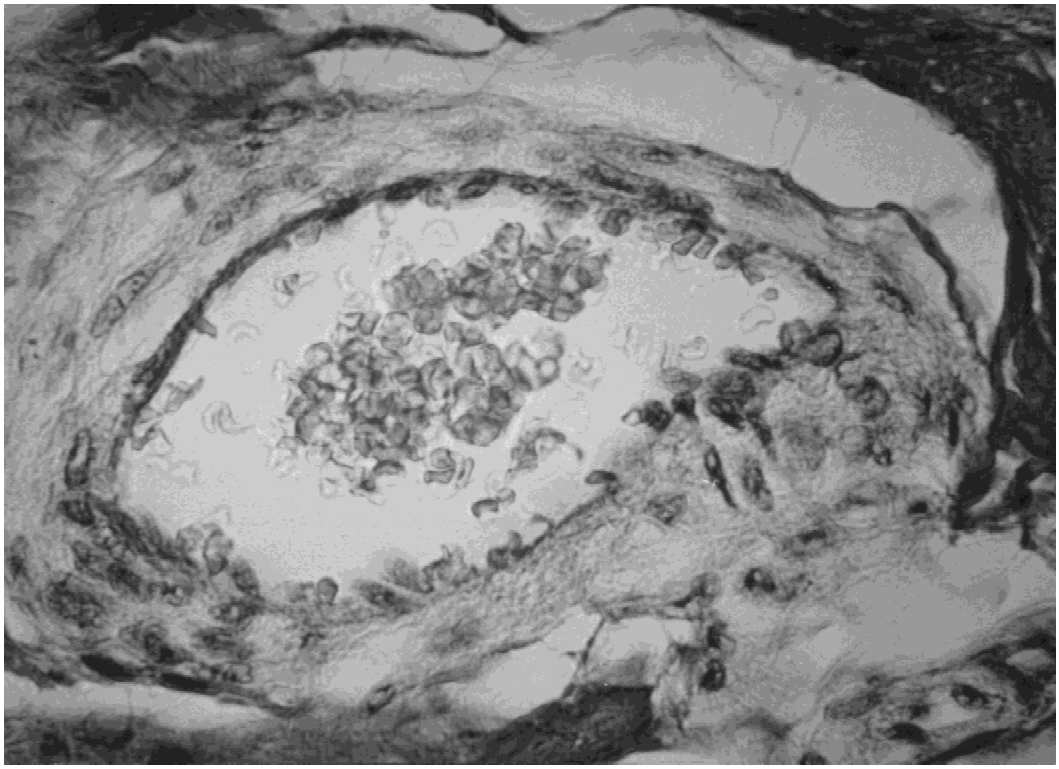

Fig. 7. Patent coronary vessel surrounded by fibrous tissue in a laser-induced scar showing unchanged media and endothelium, no thrombi in its lumen.

tory infiltrates were conspicuous, sharply demarcated by the surrounding unchanged vital myocardium. The 3–28-month-old chronic lesions showed white scars of collagenous connective tissue. Patent coronary vessels with unchanged media and endothelium were found within the scars (Fig. 7).

DISCUSSION

Various forms of experimental laser ablation of ventricular myocardium have been studied so far. Good initial results have been reported with intraoperative argon laser ablation of ventricular tachycardia [9]. However, argon laser effects are closely related to surface vaporization, whereas the Nd:YAG laser is more suitable for tissue coagulation [15]. Due to its low absorption in normal and coagulated myocardium, Nd:YAG laser light has the potential of reaching deep intramural sites from the endo- or the epicardial surface [16,17]. As suggested by the apical lesions produced during this study, laser light may penetrate through scarred tissue and coagulate myocardium even across fibrous tissue. This may be the reason for the high long-term cure rate of intraoperative map-guided Nd:YAG laser coagulation in patients with VT due to myocardial infarction [10].

For nonsurgical catheter-directed laser coagulation of myocardium, a catheter system adapted to intracardiac application of laser light is paramount. Since the first intracardiac application of laser light [18,19], a variety of catheter designs have been used for ablation of ventricular myocardium [20–23]. As shown in this study, by means of preshaped self-guiding catheters, the lateral and posterior left ventricular walls can be targeted quickly. Preshaped guide catheters with curves different from those used in this study may be required for targeting other endocardial areas in the ventricles. Both the resilience of the catheter system and the tripod-like distal end of the EL-catheter with its pin-electrodes enable the operator to achieve a stable end-on position of the catheter tip upon the endocardial surface avoiding a too high pressure on the myocardial wall. Monitoring of local potentials via the pin-electrodes during laser application allows for online control of laser effects and premature termination of ineffective pulses.

Continuous wave Nd:YAG laser irradiation

as applied in this study can produce gradual, dose dependent coagulation of the irradiated myocardial region. Even transmural lesions can be achieved, if desired, without compromising the structural integrity of the left ventricular wall. The optical fiber tip is protected within the distal catheter hose at 1.5 mm from the end hole and does not touch the endocardium, whereas the catheter hose and the pin-electrodes do. Thus laser light can be applied in a noncontact mode. Both the distance from the irradiated surface and the adapted beam divergence allow for maximizing the laser spot, reducing the irradiance and, thereby, the risk of overheating. In addition, noncontact irradiation allows for flushing of the entire irradiation field by the flow of cooling saline. This may substantially contribute to the efficacy of the method and to the preservation of the anatomic integrity of the ventricular walls even when laser pulses of up to 60 s were applied and transmural lesions of coagulation necrosis were achieved. The audible pops that occurred during some of the laser pulses did not cause rupture of the endo- or epicardium and are probably due to release of intramural steam. This phenomenon could be ruled out by powers limited to 20 W or less. At 20 W, a higher amount of energy could be deposited than at 30 W and larger lesions were produced without untoward effects on the myocardial walls. In conclusion, volume of coagulated myocardium should be maximized by increasing rather pulse duration than laser power.

Study Limitations

In this study laser lesions were produced in healthy and scarred canine hearts and not in diseased ventricular myocardium of humans. Laser-induced scars do not represent a true infarction model and do not resemble the entire spectrum of diseased ventricular myocardium in humans. Delivering laser energy to diseased human myocardium may result in an irregular lesion shape and greater variation in lesion size.

Clinical Implications

The results of this study indicate that noncontact transcatheter Nd:YAG laser coagulation of ventricular myocardium can be performed in a safe and controllable manner when using the EL catheter system as described. Transmural lesions can be produced through normal and scarred myocardium without compromising the anatomic integrity of the ventricular walls. Recently, we have demonstrated that Nd:YAG laser catheter irradiation of canine myocardium produces deeper lesions, in a more controllable manner and with less endocardial damage than radiofrequency current application (24). Based on these promising experimental results and our successful clinical experience with laser ablation of supraventricular arrhythmias, we have recently extended the laser technique on candidates for ablation of VT including patients with diseased myocardium.

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